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A thermodynamic review on solar box type cookers

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ABSTRACT

Globally there is profuse literature on the continuous developments of box type solar cookers and solar ovens. A lot of research work has been carried out in recent passed years in the world which clearly shown the utilization of solar energy towards the greatest needs of mankind obviously solar cooking, fuel saving, non-polluting environment and to save and produce electricity. In the present literature the efforts have been made to focus on diverse developments of box type solar cooker till now. An attempt has been made to optimize the various major parameters such as geometries of box-cooker, glazing system, cooking vessels design, heat storage, insulation, mirror boosters and financial feasibility of solar cooker box. All the discussed factors have been taken into account in the fabrication of a simple solar box cooker and a good improvement has been found in the performance of box cooker with efficient working in low ambient temperatures. A wiper type mechanism to remove vapor droplets from the bottom of glazing, during the cooking process has been introduced and discussed with a new designed cooking vessel. The investigational testing of the fabricated box cooker has been carried out under the climate conditions of Moradabad (latitude – 28°58′north and longitude – 78°47′east) Uttar Pradesh.

Contents

Abbreviations: SBC, solar box cooker; FPC, flat plate collector; PCM, Phase Change Material; CPC, compound parabolic concentrator; PSC, parabolic solar cooker; GHE, Green House Effect; GHG, green house gasses; SBCI, Solar Box Cookers International; TIM, transparent insulating materials; TES, thermal storage system; IMC, internal model control; OPB, oil pebble bed; PPB, packed pebble bed; PBP, pay back period; SHS, sensible heat storage; LHS, latent heat storage; BIS, Bureau of Indian Standard; VTC, vacuum-tube collector; ASAE, American Society of Agriculture; I.E., instrumentation error; ANN, artificial neural network; NPV, net present value; TES, thermal energy utilization; Q.C., quality control; NEDA, Non-Conventional Energy Development Agency.

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Nomenclature

Symbols

A	aperture area of absorber tray (mm^2)
C_w	specific heat of water (kJ $kg^{-1}/{}^\circ C$)
F_1	first figure of merit ($m^2\,{}^\circ C/W$)
F_2	second figure of merit
H_S, H	solar radiation (W/m^2)
M_w, m	mass of water (kg)
C_w	specific heat of water (J $kg^{-1}\,{}^\circ C^{-1}$)
C_p	Specific heat of cooking utensils (J $kg^{-1}\,{}^\circ C^{-1}$)
P	cooking power (W)
P_s	standard cooking power (W)
T_{cv}	temperature of cooker with conventional vessel (°C)
T_{nv}	temperature of cooker with new vessel (°C)
T_{W2}	final water temperature (°C)
T_P	plate temperature (°C)
T_{Stag}	stagnation temperature (°C)
T_{amb}	ambient temperature (°C)
T_{oven}	stagnation temperature of solar oven (°C)
U_t	top heat-loss factor of a SBC
U	overall heat loss coefficient
U_{tw}	top heat loss coefficient (water loaded cooker)
T_{amb}, T_a	ambient temperature (°C)
$T_{stsg\text{-}A}$	stagnation temperature in cooker "A" (°C)
$T_{stsg\text{-}B}$	stagnation temperature in cooker "B" (°C)
$T_{w\text{-}A}$	water temperature in cooker "A" (°C)
$T_{w\text{-}B}$	water temperature in cooker "B" (°C)
T_{cv}	water temperature in conventional cooking vessel (°C)
T_{nv}	water temperature in new cooking vessel (°C)
W_{rt}	with respect to
R	reflector tilt angle

Greek symbols

ΔT	temperature difference
τ	time difference between readings, Seconds
η	cookers efficiency
α	absorptivity of receiver surface
β	transmission coefficient of window
α'	elevation angle of the sun

1. Introduction

1.1. History of solar cooking

Solar cooking actually has some pretty early recorded beginnings starting with the documented efforts of French-Swiss Physicist Horace de Saussure in 1767. As for solar cooking in the United States the movement did not have much of a presence or a foundation until about the early 1970s, although there were some scattered documentations of cases of individuals who had built and used solar cookers for experimental and entertainment purposes as far back as the 1940s and 50s. The most recognized first real individual in the United States is considered to be Barbara Kerr of Arizona. She is attributed with having designed and developed the first feasible and functional box style solar cooker in the US. Principally solar cookers and ovens absorb solar energy and convert it to heat which is captured inside an enclosed area. This absorbed heat is used for cooking or baking various kinds of food. In solar cookers internal box temperatures can be achieved up to 200 °C. Solar cookers come in many shapes and sizes, for example there are: box cookers, concentrating-type or reflector cookers, solar steam cookers, etc. This list could go on forever. Designs vary, but all cookers trap heat in some form of insulated compartment. In most of these designs the sun actually strikes the food for cooking [1–4] (Table 1).

1.2. Types of solar cooker

Solar cookers have been classified into four main categories: (a) concentrator type cookers; (b) solar ovens; (c) box type cookers; and (d) indirect solar cookers. Even these four main categories have been further subdivided into different categories (Fig. 1).

A lot of developments and modifications have been made to various types of solar cookers but characteristically modifications have been made to box type cookers due to its straightforwardness and users responsive. If we talk about the work on the box cooker mostly work carried out in this area is limited to only for research purpose. Many designs have been made to box cookers but how many of them are currently in used worldwide? A very few individuals have been worked to solve the problem purposely i.e., use of sun energy in mankind as for cooking, water heating, drying, etc. A glimpse of various contributions in cooking technology through SBC has been presented in the present review article.

2. Geometry of solar cooker

A SBC is basically an insulated box with a transparent glass cover and a top lid which has a mirror booster on the inside to reflect sunlight into the box when the lid is kept open. The inner part of the box is painted black. Up to four cooking vessels are placed inside the box with the food to be cooked [20,21]. It is all the elements and parameters have a great importance and effects very much on the thermal performance of box cooker. It has proven by the various modifications and developments in most elements of box cooker, which have resourcefully improved the efficiency and performance of cooker box (Fig. 2).

2.1. Booster mirror

In the field of solar cooking the use of mirror boosters, reflectors and concentrators is carrying out since the beginning. The addition of side mirror boosters can increase the output of solar FPC's to permit higher working temperatures and enhance the efficiency. Side mirror improves the performance of a SBC by reflecting the extra solar radiation on the aperture area and thus reduces the cooking time. Supporting mirror boosters depends greatly upon the incidence angle. Mirrors are used to get the extra solar radiation become less effective when the solar incidence angle increases and more effective when the mirror angle changes according to the position of sun. The use of side mirrors in a SBC makes possible cooking of food in low ambient temperature [22].

Tabor investigated that the addition of face and side mirrors used to increase the amount of radiation on the FPC are the reten-

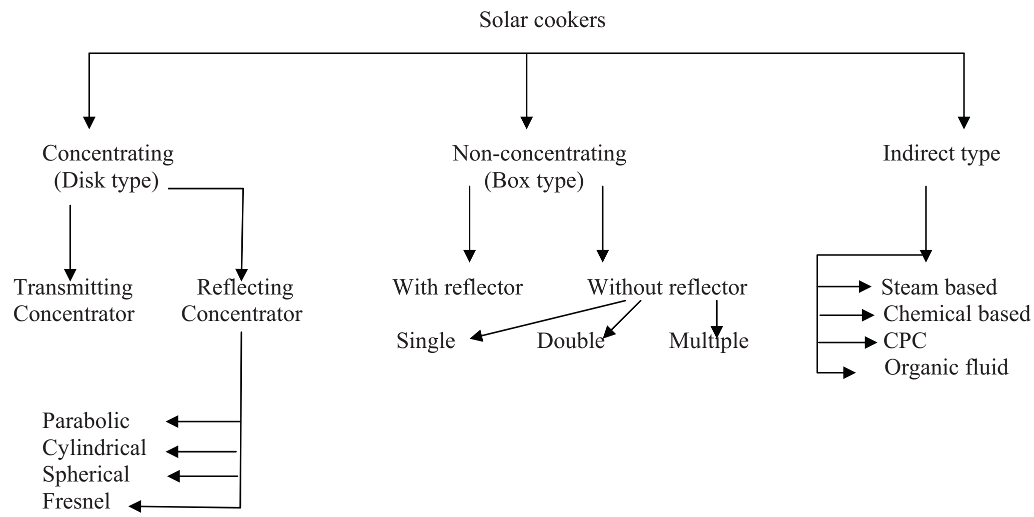

Fig. 1. Types of solar cookers.

Table 1
Contribution of some legendary researchers in solar cooking [1–19].

Journey of solar cooking, from 1767 to 2000	
1767	Saussure's was made efforts to cook food by sun energy. He built a small greenhouse with 5 layers of glass boxes turned upside down on a black table and reported cooking fruit
1830	English astronomer Sir John Herschell cooked food in a similar insulated box on an expedition to South Africa
1860	Augustin Mouchot was the first to combine the box/oven heat trap and burning mirrors concepts to create a solar cooker/oven. He saw great commercial potential in France's sun-rich, fuel-poor colonies in North Africa and Asia
1876	In India, W. Adams developed an octagonal oven with 8 mirrors which cooked food for 7 soldiers in 2 h. Dr. Charles G. Abbot, Secretary of the American Smithsonian Institution, was the first recorded inventor of solar cookers in which the heat collector was outside but the cooker was inside house, with heat carried from collector to cooker by circulating oil
1877	Mouchot devised solar cookers for French soldiers in Algeria, including a shiny metal cone, made from a 105.5° section of a circle. He built a separate cooker to steam vegetables and also wrote the first book on Solar Energy and its Industrial Applications
1884	Another Smithsonian scientist, Dr. Samuel P. Langley, solar cooked meals atop Mt. Whitney in California
1894	Xiao's Duck Shop in Sichuan, China, roasted ducks by solar cooking
1930s	India began to investigate solar energy as a substitute for dwindling wood and depletion of soil from burning crop residues and dung
1940s	Dr. Maria Telkes in the U.S.A. researched several combination types of solar cookers, including some with heat retention chemicals and published a book, Solar Ovens, in 1968
1945	Indian pioneer Sri M.K. Ghosh has been designed the first solar box cooker to be commercially produced
1950s	Indian scientists in government laboratories designed and manufactured commercial solar cookers and ovens, but they were not readily accepted, partly because there were still lower-cost alternatives. Farrington Daniels and George Löf at the U. of Wisconsin, USA, introduced concentrator cookers in northern Mexico, with some acceptance
1955	The International Solar Energy Society (ISES) began as the Association for Applied Solar Energy, whose first conference in Phoenix, AZ, USA, introduced many practical solar cookers. By then the technical basics of solar cooking were known. Exhibited solar cookers included parabolic by M.L. Ghai of India, Georg O.G. Löf (US), Adnan Tarcici (Lebanon) and S. Goto (Japan) and box cookers by Maria Telkes (US) and Freddy Ba Hli (Burma)
1961	A United Nations Conference on New Sources of energy included many types of solar cooker pioneers, including, M. Telkes, Löf, Duffie, Pruta and Abu-Hussein
1970s	Spreading deforestation prompted research and promotion of solar cooking by governments of India and China. A fuel shortage temporarily created new interest in renewable energy worldwide
1973	Barbara Kerr, USA, built many types of concentrating and box solar cookers from descriptions, including Ghosh's box cooker in India. She used simplest materials inspired by retained heat cookers ('hay boxes') and developed low-cost, simple solar cookers using recycled materials and aluminium foil
1978	Kerr and Cole began small-scale production and promotion of solar cookers and planed for people to make their own. Prof. Metcalf learned about Kerr–Cole cookers through Fred Barrett, U.S.D.A, bought one, and immediately became a regular user and began research on their germ-killing capacities. Hurry he became a promoter of solar cookers both in the Sacramento area
1980s	The governments of India and China expanded national promotion of box cookers. A lot of researches have been carried out in this era. Brace Research Institute, McGill U., Canada, researched and field tested solar cookers. Prof. S.S. Nandwani in Costa Rica researched solar cookers. Box cookers were distributed to 20,000 Afghan refugees in Pakistan by SERVE (Serving emergency Relief and Vocational Enterprises). M.H. Gurley Larson wrote first U.S. solar cookbook, Solar Cooking Naturally, in'83 Metcalf. In'84 Metcalf published his 9-page instructions for building solar box cookers. ULOG was started by Ulrich and Lisel Oehler to promote box and parabolic cookers in many countries. With Kerr–Cole instructions, solar cookers were built in Kitui, Kenya in'85
1987	In India, Mullick, et al. carried out the thermal evaluation of box-type solar cookers and generated two figures of merit (F_1 and F_2) to find out the cooker's performance
2000	Dr. Paul Funk proposed an international standard in terms of cooking power (W) for testing solar cookers and reporting performance was applied to historical solar cooker test data to show that it is a useful tool for evaluating the relative performance of dissimilar designs. Accepted also by ASAE

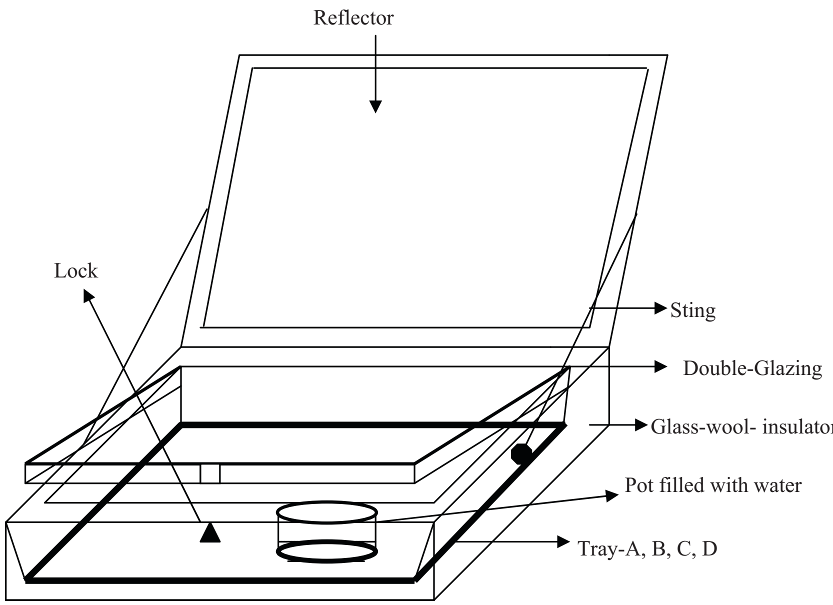

Fig. 2. A schematic diagram of solar cooker box type.

tion efficiency N (ratio of energy yield to energy reaching and absorbed by collector) is a more basic characteristic of collectors than the collection efficiency even though they are related by $\eta = (\alpha,\beta)\,N$ because (α,β) varies during the day, so the concept of "filtered" sunshine was introduced. Various curves were drawn which proved the mirror boosters in addition has a good enhancement of efficiency of solar collectors [23]. Dang has been explained that flat mirrors have been used to boost the performance of a FPC with a basic reason for their increasing utilization, is that solar radiation after getting reflected from boosters may enhance the heat collection. The symmetric booster mirrors produce a flux concentration ratio of 2.0. The efficiency of a booster flat plate system can be increased if the angle of plane reflectors can be changed several times changing the years [24]. Garg and Harishkeshan have been carried out a comprehensive analysis of a FPC augmented with two reflectors. The model was numerically simulated for conditions prevailing in three different Indian stations (Madras, Pune and Delhi) for three different months. The enhancement was the maximum for December in all three stations for both horizontal and tilted surfaces. For the month of December total energy on collectors shown an increment with respect to increase in latitude [25].

Narsimha Rao et al. made some nice efforts to get store the maximum heat energy reflected by mirror boosters. An analysis of the effect was made by providing an adjustable mirror booster, hinged on a SBC towards the south face. The calculations for total energy falling on the collector area were made for altitude of 18°N (Warrangal city, India) and for five different declinations of the sun. By intermittent adjustment, continuous adjustment and fixed orientation of the single mirror booster the total energy was improved at all hours of the day. The effect of elongation (ratio of long/width of aperture) of rectangular apertures, provided with a single mirror booster, on the energy collection was investigated. It was noticed that the rectangular aperture with booster mirror had higher specific energy collection when compared with similarly booster square aperture. In the case of horizontal aperture the rectangular apertures were more efficient than the equal area of square aperture, when the total energy collected was criterion. The efficiency was almost a constant for a value of elongation. It was analyzed the energy accretion pattern of a SBC with a plane mirror hinged on northern edge was made. It was discussed that with an increase in latitude the energy contribution from the mirrors becomes significant in relation to the energy intercepted by the aperture directly and mirror became much more effective during winter solstice ($\delta = -23.45^\circ$) at higher latitudes [26–28].

Narsimha Rao et al. have discussed an algorithm to asses the contribution of a solar energy on a horizontal receiver by plane booster mirrors. A FORTAN computer code had been prepared on the base of algorithm which was used to evaluate the contribution from the booster mirrors in different orientations and tracking modes. The south facing mirror was found to be best for energy boosting especially at lower solar altitudes. This algorithm is flexible enough to allow the study of solar devices such as solar cooker and solar stills [29]. El-Sebaii et al. designed and constructed a SBC with multi-step inner reflector in lower, middle and upper side in manner to create angles of 30°, 45° and 70° W_{rt} horizontally, respectively. A glazing of 25 mm gap was used. Cooking vessel was resting on a specially designed holder. A mathematical model was developed to investigate the transient performance of a SBC. The overall efficiency of the cooker was found 30% [30]. Habeebullah et al. have discussed, if the box cooker is surrounded with four mirror reflectors then wind losses will be reduced because wind will not be in direct contact to the glazed surface. An oven type approach was introduced as an alternate for collecting the solar energy would drastically boost the overall cooker efficiency. A mathematical model was developed to solve energy equations by the help of Forth order of Ranga–Kutta method. A great advantage to use a glass sided solar oven over the base receiver pot was shown theoretically by simulation. The oven type receiver has proven to be practically independent of wind speed [31].

EL-Sebaii and Aboul-Enein were presented a transient mathematical model based on analytical solution of the energy-balance equations using Cramer's rule for different elements of the box cooker. All the experiments were carried out in Tanta, latitude 30°47′N, Egypt. The model was discussed for a SBC with a one-step outer reflector hinged at the top of the cooker. The characteristic boiling time was found decreased about 30%, when the cooker was used at mid-day [32]. Algifri and Towai has been outlined a method to find out a reflector performance factor and an orientation factor that depend upon the elevation angle of the sun, the solar surface azimuth angle and the reflector tilt angle. The analysis was applied to a SBC placed at Aden (Yemen) and discussed if

the cooker satisfied a relationship between the reflector tilt angle and the elevation angle i.e., $3R - 2\alpha' = 180^{\circ}$ then cooker has given its best performance. During winter season the cooker was noticed more efficient [33].

Mirdha and Dhariwal have been hypothetically investigated various designs of solar cookers with a view to optimize their performance. Various combinations of booster mirrors have been studied to enter at a final design, aimed at providing a cooker, which can be fixed on a south facing window. Certain changes in positions of the side booster mirrors without moving the cooker as a whole has been proposed for higher temperature throughout the day and round the year [34].

2.2. Glazing

Glazing materials include glass, acrylics, fiberglass, and other materials. Although different glazing materials have very specific applications and the use of glass has proven the most diverse. The various types of glass allow the passive solar designer to fine-tune a structure to meet client needs [35]. The single pane is the simplest of glass types and has a high solar transmission. Single pane glass can be effective when used as storm windows, in warm climate construction for certain solar collectors and in seasonal greenhouses. Structures using single pane glass will typically experience large temperature swings, drafts, increased condensation, and provide a minimal buffer from the outdoors. Perhaps the most common glass product used today is the double pane unit. Double pane glass is just that: two panes manufactured into one unit. Isolated glass (thermopane) incorporates a spacer bar (filled with a moisture absorbing material called a desiccant) between the panes and is typically sealed with silicone. The spacer creates a dead air space between the panes. This air space increases the resistance to heat transfer. In fact, a large air space can actually encourage convective heat transfer within the unit and produce a heat loss. A rule of thumb for air space is between 1 and 2 cm [36–38].

Mullick et al. have considered a double glazed box cooker and a double glazing with suitable thickness and gap in between were found better than a single thick glazing. The proposed method can be used to develop correlations for the U_t of a SBC by suitable conducting tests [39]. Akhtar and Mullick developed an improved equation form for computing the glass cover temperature of FPC with single glazing. A semi-analytical correlation for the factor "f" the ratio of inner to outer heat-transfer coefficients as a function of collector parameters and atmospheric variables was obtained by regression analysis. This relation readily provided the glass cover temperature (T). It covers a broad range of variable i.e., air gap spacing 8–90 mm and T_{amb} 0–45°C. The maximum error in calculation of U_t by present method in the comparison to that obtained by numerical solution of heat balance equation was estimated about 2% [40].

Bell has highlighted the glazing selection for various heat transfer applications. One or more sheets of glass or other diathermanous (radiation-transmitting) material is used to transfer the sun energy in to the collector/absorber plate. The transparent cover (glazing) is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. It also reduces radiation losses from the collector as the glass is transparent to the short wave radiation received by the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate [41,42]. Kalogirou has discussed the use of solar energy in the various types of solar collectors including flat-plate. The glazing should admit as much solar irradiation as possible and reduce the upward loss of heat as much as possible. Although glass is virtually opaque to the long wave radiation emitted by collector plates, absorption of that radiation causes an increase in the glass temperature and a loss of heat to the surrounding atmosphere by radiation and convection. Transparent insulating materials (TIM) were recommended to enhance the performance of solar collectors, which can be filled in double or triple glazing [43,44].

2.3. Absorber tray

Absorber tray of a box cooker is a simple FPC. When solar radiation passes through a transparent cover (glazing) and impinges on the black painted or coated absorber surface of high absorptivity, a large portion of this energy is absorbed by the tray and then transferred to the food to be cooked placed in the cooking vessels inside the cooker [45,46].

Pande and Thanvi introduced a new design of SBC that was found more practical in comparison to the simple box cooker. The inner box was designed in a step fashion with a width of 11.5 cm of each step. The cooker was fixed on the flexible iron angle stand to keep the system of optimum tilts in different seasons. It was estimated that the cooker would save 35–40% of the cooking fuel with the use of such type absorber [47]. Shrestha have calculated that one glass cover with selective coating on absorbing tray is much better than two glasses glazing with a simple black coated absorber tray. The four different models were prepared and with the help of heat flow charts and presented a mathematical model [48]. Thulsi et al. has examined and explained the various heat transfer rates in the SBC's, like thickness of the plate, numbers of the pots used, the black paint on the pots and reflectors. It was shown that 0.5–1.0 mm plate thickness reduced the radiative and convective heat transfers through a mathematical model and simulation [49,50].

Tripanagnostopoulos and Nousia have tested various colors for selective coating on the absorber surfaces/trays to absorb the maximum heat energy. The collector tray absorbs as much of the irradiation as possible through the glazing, while loosing as little heat as possible upward to the atmosphere and downward through the back of the casing. The absorptance of the collector surface for shortwave solar radiation depends on the nature and color of the coating and on the incident angle. Various color coatings have been proposed over the solar collectors/absorbers while the black is usual [51].

Amer modified a double exposure solar cooker in which absorber was exposed to solar radiation from top and bottom. The cooker was tested under the Egyptian climate and reached to 165 °C, a stagnation temperature. It reduced the cooking time about 30–60 min W_{rt} conventional type SBC [52]. Kumar carried out a simple thermal analysis to evaluate the natural convective heat transfer coefficient, h_{c12} for a trapezoidal absorber plate inner glass cover enclosed space of a double glazed SBC. The results of h_{c12} were compared with those of rectangular enclosure for the same absorber-inner glass cover temperatures and gap spacing. U_t was found to be lower by 7% in the case of a rectangular enclosed space. The major advantage of using a trapezoidal shaped absorber tray in a SBC is the absorption of a higher fraction of incident solar radiation falling on the aperture at larger incidence angles, due to a more exposed surface area [53]. Ogunwole developed a SBC made off a casing and an absorber which was blackened and made of stainless steel. Aluminium foils were used as reflectors. The shape of the casing was trapezoidal; the first layer was inserted into second layer and filled with local sponge of 55 mm. Angle of inclination, horizontally was 72°. This type of cooker was found good for the pasteurizing and other purposes [54].

Agami Reddy has explained that absorber is the most complex portion of the FPC and a great variety of configurations has been currently available for solar collectors. Some of the likely concepts in absorber design for most types of absorbers were discussed for better performance of FPC. Conventional materials are copper, aluminium, and steel. The absorber should be either painted with a dull black paint or can be coated with a selective surface to improve

performance [55]. Harmim et al. carried out some experiments to compare experimental performance of a SBC equipped with a finned absorber plate to a SBC carrying absorber plate without fins. Tests have been carried out in the desert of Algeria at Adrar (latitude 27°53′North and longitude 0°17′West). Fins that have been used in solar air collectors enhanced heat transfer from absorber tray to air. The results of the experimental investigation have been carefully analyzed and shown that the T_{stag} for a SBC equipped with a finned absorber plate was about 7% more than a SBC with an ordinary absorber tray. The cooking time was found to be reduced about 12% with a finned absorber tray [56].

2.4. Cooking vessels

Usually cylindrical shaped cooking vessels made of aluminium are used for cooking in a SBC. The outside of vessels is coated black and attached to the centre of the absorber plate to achieve the desired contact between the pots and the absorber plate; in order to increase the rate of heat transfer by conduction between the absorber plate and the cooking vessels. The number of vessels can be varied according to quantity and nature of food.

Khalifa et al. have conducted some experiments on an Arafa cooker, basically a point focus concentrator that featured with Pyrex pots. The tracking was done manually for every 15–20 min. During the investigations it was found out that heating off many food items by the directly reflected solar radiations results in reasonable cooking time. A Teflon coated black aluminium plate inside the Pyrex pots was utilized for absorbing the incoming radiation and to collect the energy in large quantity [57]. Guar et al. have been modified the lid of a utensil by taken it into a concave shape instead of flat shape and by using this modified lid the time of cooking was reduced to 10–13%, than that time taken by a utensil with normal flat lid. Water was taken as a cooking fluid [58].

Narasimha Rao and Subramanyam used vessel on lugs for solar cooking and shown that if lugs are used to keep the vessel in a SBC, the circulation of hot air but the top of surface a bottom of vessel improve the convective heat transfer to the contents in the vessel and cooking time might be decreased. In this case the losses through the wind velocity can disturb the beam incident and repositioning of concentration is time taken. It was also found that the cooking time was reduced through providing a central annular cavity in the cooking vessel (both in pot and lid). A cylindrical hole reduces the heat transfer of heat to the cooking fluid to be cooked and kept in vessel. The vessel was kept on the lugs inside the SBC. The cooking time was noticed less than using a conventional vessel [59,60]. Reddy and Narasimha Rao have developed a cooking vessel with a cylindrical central cavity. It was tested for cooking and compared to conventional type of cooking vessel. The study of performance of vessel was carried out for lugs an absorber tray. An improvement was found out in the performance of cooker for 5.9% and found 2.4% more than that of a conventional cylindrical vessel [61].

Srinivasan Rao made some modifications in the previous design [5] of cooking vessel. The externally supported fins were provided to the cooking vessel with central annual cavity to increase the heat transfer to the cooking vessel. Experiments were conducted with a conventional cooking vessel and new designed cooking vessel. The fins were rectangular in shape and attached inside the cavity. The central cavity hole reduces the heat transfer path length and facilitates the better heat transfer to the fluid to be cooked in the vessel. A maximum temperature gain of 17 °C was observed with new design of cooking vessel in comparison of conventional type [62]. Harmim et al. have fabricated and tested a double exposure SBC carrying a specially designed cooking pot with fins on the outer joint of lid. A parabolic reflector was a section of a linear parabolic concentrator, which was made of a wooden frame and rectangular glass mirrors were fixed on it for boosting. The vessel was made of aluminium and painted black [63].

2.5. Insulation

It is essential for the solar thermal applications to store the heat energy maximum for efficiently working. To prevent the transmission of heat energy from inside the box to the outside the box, providing insulation is mandatory [64–66]. Most of the heat loss in a box cooker is through the glass or plastic in comparison of the walls. This is why insulation is necessary in between the wall of the frame box and absorber tray as well as in glazing. It affects great, the overall temperature and cooking power of a SBC.

Thulasi Das et al. have considered the insulation thickness of 7.5 cm as adequate. This prevents heat from escaping from inside the SBC. The filling material can be glass wool, paper rolls, hay, straw, etc. Whatever material is to be used it should be dry and should not be filled too forcefully. The reason for putting in this material is to prevent the air between the boxes from moving, as still air is a very good insulator in itself [47]. Nahar has carried out some performance testing on a hot SBC in an indoor solar simulator with covers consisting of 40 and 100 mm thick TIM. The T_{stag} with the 40 mm TIM was found to be 158 °C, compared with 117 °C without the TIM. The corresponding ratios of U/η_o were 7.13 and 10.3 W/m^2 K, respectively. Latterly he introduced a transparent insulation material (TIM) with a double reflector cooker and compared the solar cooker without TIM. Energy saving by using this cooker was estimated as 1485.00 MJ of fuel equivalent per year. A 40 mm thick honeycomb made of polycarbonate capillaries was encapsulated between two glazing sheets of the cooker to minimize convective losses from the window so that even during an extremely cold but sunny day two meals can be prepared which is not possible in a hot box solar cooker without TIM. The efficiencies were 30.5% and 24.5% for cookers with and without a TIM respectively. The energy saving by use of a solar cooker with TIM was estimated to be 1485.0 MJ of fuel equivalent per year [67,68].

Pejack has concluded that in order to reduce the heat loss from a SBC, the walls can be made thicker to increase thermal resistance and then insulated with materials which have low thermal conductivities. Glass-wool, foam, fiberglass, corkboard, wool felt, cotton, sawdust and paper all have thermal conductivities similar to that of air, .03–.06 W/m/°C and make good insulators for the walls of a SBC. The cooker can be insulated from the top by using two plates of glass with a small gap between them. The air between these plates will prevent heat from escaping back through the glass hence increase the efficiency [69].

Mishra and Prakash have summarized that the thermal performance of solar cookers with four different insulations is readily available in rural areas. A comparison of each one of them was made with the performance of glass wool. Experimental testing was carried out to minimize the cost of the cooker with a view to enhance its widespread application in the rural Indian environment [70]. Folke Björk and Tomas Enochsson have investigated three different insulators: (i) Moniflex, (ii) glass wool and (iii) melamine foam to study the properties of condenses formation, drainage and moisture dependent heat transmittance. Among three insulators glass wool had the biggest condense formation. Materials were found best suitable for insulation in dry form [71].

3. Various designs of solar cooker

In the past, various designs of solar box type cookers have been theoretically and experimentally investigated with a view to optimize their thermal performance and efficient cooking.

Malhotra et al. have tested four solar ovens with different volumes and fabricated for performance study. It was experimentally observed that the reduced volume of a cooking chamber results in a good temperature rise and the results in less cooking time as well as possibility of cooking most eatables [72]. Khalifa et al. modified a commercial version of the oven to feature a vapor tight cooking pot that was thermally bonded to a single glazed collector plate. The characteristic water boiling time of about 24 min-m^2/kg was successfully achieved by the Mina oven. The cooker efficiency was found 27% with the cooking capability of three meals a day [73]. Nahar has designed a multipurpose solar cooker and reported performance testing of an improved solar water heater cum steam cooker. The efficiency of the system as a solar water heater was 51.5% and as a solar steam cooker was 16.1% [74]. Tiwari and Yadav have designed a SBC with a single reflector. In this design, the base of the base of the oven acts as lid to solve the problem of pre-heating as facing in a conventional SBC. The lid at the top allows convective heat transfer losses on raising the lid and could be situated at the base of the oven, the convective heat transfer would naturally be reduced. The newly designed cooker was found more efficient than conventional cooker [75].

Pande and Thanvi introduced a new design of solar cooker which was found more practical in comparison to the simple box cooker. The inner box was designed in a step fashion with a width of 11.5 cm of each step. The cooker was fixed on the flexible iron angle stand to keep the system of optimum tilts in different seasons. It was estimated that the cooker would save 35–40% of the cooking fuel [47]. Khalifa et al. have developed a new oven cooker that permitted heating from the bottom and sides. Simulation studies were conducted for predicting the thermal performance of that cooker for which concentrated solar energy would be supplied via a spiral concentrator. The new spiral cooker with the bottom glazed and insulated oven possesses the following main advantages in comparison to other solar cookers as reduced cooking time, less affected from wind and most of the foods can be cooked in short time [76]. A simple theoretical analysis was carried out by Nandwani for cooking aspects/measurements of various parameters (like oven with or with out reflector and heat loss coefficients). The solar oven was constructed with simply available materials for a cost around US$30–35, and successfully operated for cooking for a duration of seven months in a year in the climate of Heredia [77].

Nahar has carried out performance study of some novel solar cookers (i). A novel device can be used as a solar water heater during winter and a solar cooker during summer. The overall efficiency of the device as a solar water heater was 62.6% and 23.8% for a solar cooker. (ii) A novel solar cooker with a tilted absorbing surface can be used so that more radiation can be obtained even during winters, therefore, two meals can be prepared in winters, while only one meal was possible in the SBC because it has a horizontal absorbing surface. The overall efficiency of this improved cooker was 24.6%. (iii) A large size non-tracking solar cooker, based on the hot box principle. The former was not tracked towards sun while the latter was tracked every 30 min. The efficiency of a large size non-tracking solar cooker was 24.9% with a PBP of 1.10–3.63 years [78–80]. Al-Saad and Jubran designed and developed a solar cooker by locally available materials; some black stones were used to eliminate the absorber tray. The material selected was clay which consists of a mixture of natural deposits formed by weathering of certain rocks. The black stones were capable to store solar energy hence making late cooking possible. The cooker was consisting of a single glazing 6 mm thickness and the side walls of cooker were built from clay bricks. No skilled labor was in need to use the solar cooker [81].

Grupp et al. have presented an advance version of a SBC with a fixed cooking vessel directly attached to absorber plate. The results were improved for thermal performance, easier access to the cooking vessel and less frequent maintenance due to protection of all absorbing and reflecting surfaces [82]. Nandwani and Gomez considered two folding and light solar ovens and experimentally tested in the climate of Costa Rica. Both the solar oven and cooker were designed by Solar Box Cookers International, Sacramento, U.S.A. and found 25% less efficient than the conventional oven but improved than previous SBCI. The tests were conducted at load and no load condition, and with or without a reflector [83].

Nahar et al. have paid some attention to utilize solar energy even for animals by fabrication and design some simple solar cooker. (i) A large-size solar cooker for animal feed was tested. A pit was dug in the ground. The clay, pearl-millet husk and horse excreta were mixed with water in an equal proportion and the paste was prepared to fill up to a depth of 50 mm in the bottom of pit. A 20 SWG mild steel absorber was put over this insulation and the absorber was painted black. The efficiency of the solar cooker was 21.8% and its capacity was 10 kg of animal feed per day. The cost of the cooker was estimated only Rs. 1200 with a PBP of 0.45–1.36 years. (ii) A novel solar cooker for boiling animal feed made of locally available material of cost free. The only commercial materials required for its fabrication were glass covers and mild steel absorber tray. The cooker was capable of boiling 2 kg of animal feed per day and its efficiency was 22.6% with a PBP of 186 days. (iii) Again the same team conducted some experiments on two simple solar cookers. One made of clay and locally available materials and the other of exfoliated vermiculite and cement tiles. The relative performance of both cookers was described with their efficiencies, a 22.6% for clay and 24.9% for vermiculite, respectively. The cookers were capable of boiling 2 kg of animal feed per day and represent the equivalent of 1350 MJ of fuel per year at Jodhpur. PBS's for solar cookers made of vermiculite tiles vary from 0.50 to 3.47 years; depending upon the fuel they replace [84–86].

Wareham developed a SUNSTOVE, an affordable, easy-to-use, light-weight rugged solar cooker. The SUNSTOVE's sides were "winged" out to increase the solar collecting area to compensate for the elimination of reflectors and to reduce the internal volume to be heated. The sloped internal walls of this "hot box" reflect, radiate and conduct the sun's energy to the black cooking pots. The SUNSTOVE was an inverted partial polyhedron, pyramid or cone tilted towards the sun with solar collection area sufficient to collect enough energy to cook 6–8 l of food. The clear polycarbonate cover was sloped to collect, retain and direct the maximum solar energy to the black pots in all seasons [87]. Beaumont et al. have developed an ultra low cost solar hot box cooker which consists of a shallow 1 m^2 square hole in the grooved, lined with an adobe and insulated with the straw. The cooker was able to cook the meal for 10–12 people on a clear day. The cost was around £8 [88]. Suharta et al. carried out experimental comparison of three different solar cookers named HS.7540, HS7534 and HS7033 for the cooking performance. The latest design HS 5521, used 3 mm thick glass for glazing, good concentration ratio and cotton insulation. All the experimental work was carried out in the latitude 47°N at Spokane, WA on July 1998. The cooker was efficient to cook vegetable, rice even fishes. Maximum time taken was 62 min at 35 °C T_{amb}. Maximum T_{stag} was measured 202 °C [89]. Ekechukwu and Ugwuoke have designed a solar cooker carrying a steam relief hose for exit of steam (from the cooking chamber which when condensed in the chamber reduces transmissivity of the cover renders) the equipment untidy and may corrode the absorber plate. The hose was passed through the sidewall and it relieves steam into the atmosphere. The solar cooker performance was improved greatly with the plane reflector in place [90].

Sonune and Philip have developed a combined concentrating/oven type solar cooker. The cooker makes use of both concentrator and FPC principles, wherein the sunlight entering the cooker reflected onto a hood which was provided with a selective

solar absorber coating which houses the cooking vessels to collect total radiation. The new cooker has been found to be more practical in comparison with either the simple SBC. The cooking trial shows that the new device can be used twice a day, even on winter days [91]. El-Sebaii and Ibrahim constructed a box-type solar cooker with one (Model I) or four (Model II) cooking pots, tested under Tanta existing weather conditions. The cooking power P was correlated with the temperature difference ΔT between the cooking fluid and the ambient air. Linear correlations between P and ΔT had correlation coefficients higher than 0.90 agreeable the standard. The obtained values of the initial cooking power, heat loss coefficient and the cooking power at a temperature difference of 50 °C agree well with those obtained for small solar cookers. The developed cooker found to cook most kinds of food with an overall utilization efficiency of 26.7% [92]. Rachel Martin et al. was objected to help committees in the developing world design solar cooker, appropriate for their specific cultural, social, economic and environments conditions. The work was focused on parametric testing of previously constructor solar ovens and the development of new solar oven designs. The fix cooker, bowl cooker, cone cooker, box type cooker and parabolic trough type cooker were designed and tested in fall of 2005 and the spring of 2006 in Nicaragua [93].

Nandwani designed and studied a hybrid solar food processor for various practical aspects. It can be used for cooking, pasteurizing, distillation and drying purpose. The efficiencies for each unit of use were calculated through the use of energy balance equations. This "four in one devices" was found to be a simple solution to fuel and food problem [94]. Kurt et al. have conducted some experiments on two different model box type solar cookers which were in rectangular and cylindrical geometries, constructed using the same material. Both the cookers were tested to investigate the effects of box geometries on the cooker performance. Cylindrical model was observed by having higher temperatures than the rectangular model under the same operating conditions. The thermal efficiency increased from 12.7 to 36.98% for cylindrical and 9.85 to 28.25% for rectangular model, when the quantity of water was increased from 0.5 to 1.5 kg; similarly, the characteristic boiling time was decreased from 39.56 to 14.35 for the cylindrical and 43.74 to 15.77 ($\min m^{-2} kg^{-1}$) for the rectangular model, respectively [95]. Schwarzer et al. have considered four types of solar cookers to explain their basic characteristics and tested for performance evaluation. The variables measured in these procedures were necessary to calculate parameters and to compare the thermal performance of the solar cookers. Characteristics were safety of operation to avoid burning and other risks; easiness of transportation and assembly; tracking requirements and procedures; pot access and easiness of stirring; mechanical stability; robustness and life time [96].

Kumar et al. have designed a truncated pyramid type solar cooker. It was designed for multipurpose owing the geometry of design rays hitting inside the cooker (walls) and were reflected with high intensity to downwards a higher temperature was maintained at the absorber tray (bottom side). By making an increment in the depth of the cooker the device acts as a dryer for domestic or homely purpose [97]. In continuation of work, Kumar et al. have fabricated and tested a truncated pyramid geometry based multipurpose solar device which could be used for domestic cooking as well as water heating. Cooking tests approved by B.I.S, were performed in different seasons and the device was found to meet the requirement stipulated on two figures of merit [98]. Bello et al. have fabricated a simple SBC by the simple available materials like Mahogany, Planks, Forms, Nails, Evstics, Hinge/rollers, aluminium sheets, black paints, two pains glasses, plane mirror, saw dust, screw and brown paint, etc. The cooker was tested under the climate conditions of Guinea savannah station, Nigeria. The solar cooker was estimated to 47.56% efficiency [99].

4. Cookers with thermal storages

Objects have a certain heat capacity, the amount of heat they can hold. Certain objects can hold large amounts of heat and radiate it slowly. These objects, such as bricks, heavy pans, and water, increase the effectiveness of the cooker (although they may take longer to heat up). Addition of these materials to the sides or bottom of a solar cooker can increase the heat storage of the box and enhancement in efficiency [100,101].

Galip et al. have designed and tested a SBC to track the sun in two axes in the climate conditions of Turkey. It was good to cook only the light meal like rice, eggs, macaroni, etc. A shadow stick on the glazing was used to track the sun. Engine oil was used as thermal storage and opening of the cooker was through side wall as almost in an oven. The obtained values of thermal performance and efficiency were assumed sufficient for the climatic conditions of Turkey [102]. Nahar tested a solar cooker using engine oil as a storage material so that cooking can be performed in the evening. The performance and testing of storage solar cooker have been investigated by measuring stagnation temperatures and conducting cooking trials. The maximum T_{stag} inside the solar cooker with storage material was the same as that of the solar cooker without storage during the day time, but it was 23 °C more in the storage solar cooker from 1700 to 2400 h. The efficiency of the hot box storage solar cooker was measured to be 27.5% [103].

Mawire and McPherson have developed a feed forward internal model control (IMC) structure for controlling and maintaining the outlet charging temperature of thermal energy storage system of a solar cooker consisting of a PPB in thermal contact with heat transfer fluid contained in a storage tank. The cooking system was integrated with an electric plate. A simulink model was presented for three different control tests on the system structure. A fair result shown that the discussed model was structured and could be implemented to control the outlet charging temperature of a TES under variable electrical heating power [104]. Mawire et al. have discussed an indirect solar cooker for a solar energy capture and TES system. Energy balance equations were used to model it. Two differences, first with a constant flow rate of heat transfer fluid and second carried out a constant charging temperature. A dish type solar concentrator was used to charge the OPB. Higher exergy rates were obtained at constant temperature method while a higher value of radiation was observed [105].

Sharma et al. have focused on the available thermal storage technology for solar cooker. With the help of the heat energy storage unit, food can be cooked at late evening, which is not possible with a simple hot box cooker and concluded that solar cooker with thermal storage unit is very beneficial for the humans as well as for the energy conservation [106]. Saxena has fabricated and tested a SBC with sensible heat storage. A thin layer of (1) desert sand, (2) granular carbon, (3) mixture of desert sand and carbon was spread over on absorber tray in a solar cooker box respectively to evaluate the performance of box-cooker. All the materials spread over the tray were completely sealed with a high resisting float glass and tests were conducted for different heat absorbers separately. Third one material was found to be a good SHS. Quality cooking of every type of eatable was possible in late hours [107]. Mawire et al. have described the models for OPB, TES and TEU system of an indirect solar cooker for discharging simulations. The model was validated with investigational results and reasonable agreement was obtained between simulation and experiment. The results of discharging the TES system at a constant flow-rate indicate an elevated rate of heat utilization. It was not beneficial to the cooking process since the maximum cooking temperature was not maintained during the discharging period. The controlled load power discharging method has a slower initial rate of heat utilization but the maximum cooking temperature was maintained

for most of the discharging process and desirable for the cooking process [108].

5. Cookers with phase change materials

PCM became very supportive to enhance the performance of solar energy collectors within limitations of thermodynamics [109]. So if the storage of sun energy can be provided in a box cooker then there is a possibility of cooking food in the evening and the storage will increase the utility and reliability of the solar cookers. Hence PCM is the best option to store the solar energy during sun shine hours and is utilized for cooking in late evening/night (Table 2).

6. Cookers with auxiliary modes

Solar cookers with an external power sources are able to cook most of the foods in a short time in any climate. The use of a tiny amount of auxiliary source can improve the cooking power and enhance the performance of a solar cooker with reducing the cooking time.

Nandwani has designed, fabricated and carried out experimental studies of "ESCO" electric cum solar oven in Costa Rica. The cooker "ESCO" was studied in detail for its performance by attempting several tests as without glazing, with single or double glazing and then solar energy and electric energy with or without load separately. Another quality of the "ECSO" was that the switch from solar to electric energy and vice versa was automatic. This oven was found to cook every type of food [122].

Valizadeh and Mofatteh tested a fast response type solar cooker which was a combination of compound parabolic reflector, heat pipes, low loss thermal storage battery (capable of storing 4 kW h of thermal energy at temperatures of up to 350 °C) glass to metal seals, vacuum technology and bimetal automatic switches. It was capable to store heat energy to facilitate the cooking in the evening and the night. In the design, the hot mixture was to run down through a pipe to a thermo-symphonic heat pipe whose condenser forms the hot plate of the heat pipe. A knob was used to control the heat transfer from the tank of the box cooker to the hot plate [123].

A Hay type solar cooker was fabricated by Hussein and Khan with a tilted aperture plane. An arrangement of a low cost auxiliary heating using 100 W electric bulb inside a blackened metal casing allows the carton box to reach a good cooking temperature under cloudy conditions. The aperture inclined was 10° with and 30° without auxiliary system. The cost was reduced to 30$ compared to other solar cookers available in Bangladesh [124].

Hussein et al. have made efforts to overcome the problem of solar cooking in cloudy days. A SBC was developed with an auxiliary source of energy inside it. It was done with the help of a built-in heating coil inside the cooker or a retrofit electric bulb in a black painted cylinder. Six heating elements were used in electric irons and were connected in series to generate 150 W heat from 220 V AC and were placed below the absorber tray. An electric bulb of 100 W was also used on the absorber tray. It was found that the use of auxiliary sources allows cooking on most cloudy days [125]. Chaudhuri has estimated the electrical back up for a SBC that was 160 W at the 15 °C ambient temperature, to use a SBC throughout the year but according to BIS design specifications for a solar cooker it should not be exceed 145 W [126]. Mukao and Tinarwo made an attempt to evaluate performance of a box cooker. A micro-controller was base data acquisition system and was used which had eight single ended analog inputs making that possible to simultaneously collect data from an array of at most three cookers. A computer was used to gather all the data with C^{++} programming. The efficiency obtained, was 15% and the power obtained, was 11 Watt in the weather conditions of Zimbabwe, Bindura [127].

7. Cookers with heat pipes

This device continues to find an application across a wide range of heat transfer problems. The heat pipe is a vapor–liquid phase-change device that transfers heat from a hot reservoir to a cold reservoir using capillary forces generated by a wick or porous material and a working fluid. Heat pipes undergo various heat transfer limitations depending on the working fluid, the wick structure, the dimensions of the heat pipe, and the heat pipe operational temperature [128–130]. Mostly used in water heating applications and become a supporting hand in solar indoor/outdoor cooking.

Khalifa et al. have introduced a new FPC solar cooker with heat pipes. Olive oil was used to energy transfer between the FPC and oven plate. Besides, this modifications were applied to his previous design of solar cooker i.e., Mina oven and Arafa cooker and both were discussed for indoor as well as for outdoor cooking for satisfactorily performance. Later on they have clearly demonstrated that the feasibility of solar energy in to shade of the kitchen via heat pipes. The use of an oil bath from heat pipes condenser to the pot which was first developed for the parabolic trough cooker. Two different solar cooker *Mecca-1* and *Mecca-2* utilizing the heat pipe principle, were deigned, constructed and tested. Mecca-2 cooker with triple glazing was found 19% in efficiency and could boil 1 l of water in 27 min for a solar insolation of 900 W/m^2. For *Mecca-1*, a parabolic trough concentrator with the evaporator of an integral-copper–methanol heat pipe was used. In *Mecca-2*, a FPC, with an integral copper–acetone heat pipe and insulate cooking chamber, consisted in this cooker [131,132]. Valizadeh and Mofatteh tested a fast response type solar cooker which was a combination of compound parabolic reflector, fast response heat pipes, high quality and low cost thermal insulator storage battery, glass to metal seals, vacuum technology and bimetal automatic switches which was capable to store heat energy to facilate the cooking in the evening and the night. In the design the hot mixture was to run down through a pipe to a thermo-symphonic heat pipe whose condenser forms the hot plate of the heat pipe. A knob was used to control the heat transfer from the tank of the box cooker to the hot plate [123].

Stumpf et al. have described a three collector-based solar cooking systems in which two of them had a direct single-stage heat-pipe coupling between collector and oven plate. The third system with a double-stage thermal coupling was heated by two Sydney modules. Both couplings, single and double stage, were successfully integrated in FPC and a VTC compared to other conventional cookers discussed model was complex but offered various advantages [133]. A solar cooker was fabricated by Mehmet Esen to analyze its performance with using vacuum tube collectors with heat pipes containing refrigerant as working fluid. The present model had not only metrological conditions but also thermo-physical properties of the refrigerant used. It acts like a pre-heater but due to more expensive and complexity, it is hard to operate by an unskilled person [134].

8. Thermal performance of solar cooker

The thermal performance of solar cookers can be determined by the thorough analysis of the optical and thermal characteristics of the cooker materials and cooker design or by experimental performance testing under control conditions. The thermal performance of a solar cooker is resolute partly by obtaining values of instantaneous efficiency for different combinations of incident radiation, ambient temperature, and inlet fluid temperature. This requires experimental measurement of the rate of incident solar radiation falling onto the solar collector as well as the rate of energy addition to the transfer fluid as it passes through the collector, all under steady-state or quasi-steady-state conditions [135,136] (Table 3).

Table 2
Various PCMs used for solar cooking (with maximum T_{stag}).

Authors	PCM-tested	Mode of cooking	Maximum T_{stag} (°C)
Ramadan et al. [110]	Salt hydrate	Flat-plate solar cooker	120
Haraksingh et al. [111]	Coconut oil	Flat-plate solar cooker (integrated)	150
Buddhi and Sahoo [112]	Stearic acid	Box-type solar cooker	122
Nandwani et al. [113]	Polyethylene	Hot-box solar cooker	132
Buddhi et al. [114]	Lauric acid (filled in glazing)	Box-type solar cooker	285
Murty and kanthed [115]	Acetanilide	Box-type solar cooker	135
Sharma et al. [116]	Erythritol ($C_4H_{10}O_4$)	Solar cooker with evacuated tube collector	135 (T_w)
Hussein et al. [117]	Magnesium nitrate hexa-hydrate	Flat-plate solar cooker (integrated)	140
Chen et al. [118]	Stearic acid, acetamide	Box-type solar cooker	–
Muthusivagami et al. [119]	PCM-A-164	Concentrating type solar cooker	140
El-Sebaii et al. [120]	Acetanilide, magnesium chloride hexa-hydrate	Flat-plate solar cooker (integrated)	134
Saxena et al. [121]	Stearic acid	Box-type solar cooker	145

Yadav and Tiwari found that the time required to attain the stagnant value of temperature is mainly dependent upon the heat capacity of water or the ingredient to be cooked in solar cooker. Second factor is that if the heat capacity of cooking vessels contents has greater value then the transient time will be long hence the cooking period [141]. Channiwala and Doshi generated a correlation to estimate the thermal losses of the box-type solar cooker for the performance evaluation. The top and overall heat loss coefficients for the feasible operating range of box solar cookers were tested experimentally and presented in a graphical form as a function of the dissimilarity between mean plate temperature and ambient temperature with wind velocity and number of glass covers as parameters. It was observed that increase in plate temperature and wind velocity increases the heat loss coefficients while increase in number of glass covers reduces the heat loss coefficients [142].

Jubran and Alsaad has performed an optimization parametric study using several important parameters of the cooker. The obtained results indicate that a considerable improvement in the cooker performance was attained when the cooking pot diameter was increased. The best performance improvement was obtained when the ratio of the pot diameter and the cooker width was equal to unity. On the other side, it was found that by changing the pot depth the cooker performance was not affected [143]. Nahar and Gupta described that during the conduction of experiments for heat up conduction test of a SBC; it was found that the values of second figure of merit depend upon the quantity of cooking load and observed that the values of F_2 increase exponentially with mass of water [144]. Mullick et al. made an attempt to provide some guiding principle for selecting a suitable temperature interval for determination of F_2 that it should be determined at full load and with all the standard cooking vessels, since the value is lower with lower load and a lesser number of vessels. It was explained that the top heat-loss factor (U_t) of a box-type solar cooker varies with plate temperature, wind heat-transfer coefficient and ambient temperature. A method for correlating U_t with these variables was presented for a cooker with double glazing. A set of equations was developed for correlating data obtained in indoor experiments at different plate temperatures and wind speeds. Comparisons of the computed values of U_t with experimental values show r.m.s. errors of 2.6%. The same group also explained and validated F_2 by computing this figure from experimental data by two different procedures and comparing the obtained results [145,39].

In Egypt, Mohammad recommended the small ratio of cooking vessel between height and the vessel diameter in SBC, that suitable for cooking of rice meat, fish, etc., for a small cooking ranged 1–2.5 h. Maximum inside temperature of the box cooker reached 160 °C under field conditions of Giza, Egypt [146]. Buddhi et al. conducted experiments for heat up conduction test of a SBC and found that the values of second figure of merit depend upon the quantity of cooking load and observed that the values of F_2 increase exponentially with mass of water [147]. Ozturk has experimentally evaluated the energy and exergy efficiencies of a simple and low-cost SBC. The energy output of the SBC ranged from 2.1 to 61.7 kJ whereas the exergy output ranged from 0.4 to 6.2 kJ during the same time interval. The average daily energy and exergy outputs of the SBC were 21.6 and 2.5 kJ, respectively. A linear regression was developed to find the relationships between the energy/exergy outputs, efficiencies and temperature difference. The energy efficiency of the SBC varied between 1.3 and 55.6%, while the exergy efficiency varied between 0.3 and 6% during the same period. The average daily energy and exergy efficiencies of the SBC were 18.3 and 2.2%, respectively [148].

Subodh Kumar evaluated the thermal performance of a SBC. Several indoor and outdoor experiments were performed on a solar

Table 3
Various parameters for box-cookers performance [17,18,137–140,92].

Author	Performance parameter	Expression	Recommended values
Vaishya et al. [137]	(Performance characteristic) K	$U/(\tau\alpha)_e$	≤10.0 W/m² °C
Mullick et al. [17]	(First figure of merit) F_1	$F_1 = \frac{T_p - T_a}{H_s}$	0.12–0.16 m² °C/W
	(Second figure of merit) F_2	$F_2 = \frac{F_1(MC)_w}{At} \ln\left[\frac{1-(1/F_1)((T_{w1}-T_a)/H)}{1-(1/F_1)((T_{w2}-T_a)/H)}\right]$	0.254–0.490 m² °C/W
Kammen [138]	(Parameter index) P.I.	$\text{P.I.} = \frac{\int_{t_o}^{t_i}[T_{oven}-T_{amb}]dt}{\int_{t_o}^{t_i}[T_{amb}dt]}$	1.86 (Good)
Funk [18]	(Cooking power) P	$P = \frac{T_2 - T_1}{600} mc_p$	Details not available
	(Standard cooking power) P_s	$P_s = P\left(\frac{700}{I}\right)$	45 W, at ΔT = 50 °C
Nahar [139]	(Efficiency of cooker) η	$\eta = \frac{(m_1 C_w + m_2 C_p)(t_2 - t_1)}{cA\int_0^{\theta} H d\theta}$	27.5%
Ozturk et al. [140]	(Energy and exergy), η, Ψ	$\eta = \frac{\lfloor m_w c_{pw}(T_{wf}-T_{wi})\rfloor/\Delta t}{I_t \cdot A_{SC}}$	
		$\Psi = \frac{m_w c_{pw}[(T_{wf}-T_{wi})-T_o \ln(T_{wf}/T_{wI})]/\Delta t}{i[1+(1/3)(T_a/T_s)^4-(4/3)((T_a/T_s))]A_{sc}}$	
El Sebaii and Ibrahim [92]	(Utilizable efficiency) η_u	$\eta_u = \frac{MC_w \Delta T}{\text{A.I.}_{avg} \Delta t}$	26.7% at ΔT = 50 °C

cooker to develop a correlation for the variable U_{tw} as a function of vessel water temperature, wind speed and ambient air temperature. The proposed correlation for U_{tw} was employed to obtain heating characteristic curves or predict the thermal performance of the cooker for dissimilar quantities of water, solar radiation levels and wind speeds. The investigations reveal that the pot water requires less time to reach a certain temperature with an increase in solar radiation level while it takes a longer time with higher values of load of water in the vessels as expected. Later on the author carried out a simple test for determination of design parameters to predict the thermal performance of a SBC. The necessary design parameters, optical efficiency and heat capacity of the cooker were calculated using linear regression analysis of experiment and found the critical design parameters for the prediction of the thermal efficiency of solar box cooker [149,150].

Sharma designed and tested a SBC by ASAE and BIS for testing thermal performance of box type solar cooker. Experiments were conducted at the satellite venture business laboratory, MIE University, Tsu city, Japan (longitude 136°31′ and latitude 34°44′N). The results were satisfied by the discussed standard limits. The obtained efficiency was 32.7% for the load of 3 kg of load. SBC was found feasible in Japan for the spring months. The investigation of cooking performance of a SBC was possible with good accuracy through proposed model and simulation [151]. Gayapershad et al. tested two cookers: a low-cost, low-technology Sunstove unit and the more expensive Ishisa box unit. Two of each were used, one tracked and one untracked. All cookers were simultaneously subjected to performance tests based on the International Standard Procedure for Testing Solar Cookers and Reporting Performance. The Ishisa cooker boiled water at 100 °C for tracked and untracked conditions, the tracked unit reaching this temperature in just about 20 min shorter time. The Ishisa unit which deploys external mirror panels was found to be more sensitive to non-normal angles of incidence and benefited from regular tracking [152]. Šmejkalová et al. have evaluated the impact of shape and glazing material on the thermal performance of single reflector box-type solar cooker. Two box-type solar cookers were constructed and simultaneously tested under Czech Republic weather conditions. The standardized cooking power was calculated according to ASAE S580 standard and normalized to a standard insolation of 700 W/m^2. The tests verified significant impact of shape and relatively low impact of glazing material on the solar cooker thermal performance [153].

Purohit and Purohit have explained that the losses of heat energy are likely to occur due to opening of glazing at a specified time and may be considered for performance evaluation of SBC. The I.E. analysis has been carried out, to estimate the figures of merit F_1 and F_2 for a SBC. The accuracies of different measuring instruments have taken as their least counts. Approach used, taken for flat plate collectors [154], while, Purohit has explained to Q.C. as an essential tool for a large scale dissemination of solar thermal applications. Experiments were conducted on a SBC and a PSC to estimate the instrumentation error. Precisely it was discussed that if a solar cooker is extremely good but do not fulfill the objective to certification at international level due to instrumentation error (i.e., $F_1 \neq 0.12$ but $F_1 = 0.11$) then it become unable to certify. So it is a major factor to evaluate the performance of solar cookers. In the present case study I.E. was estimated for 1–5.5% during evaluation of thermal performance of a solar cooker [155]. Lakhar and Samdarshi have discussed various parameters and a need was clarified to identify a common link between all to evaluate the thermal performance of solar cooker. Three such objective parameters were (i) T_s, (ii) reference time and (iii) heat retention duration have been identified which can provide overall performance of the cooker related to cooking [156].

8.1. Different methods and models for performance evaluation

Analyses of individual structure parts and detail parameters impact on the collector performance are needed to make the decisions on efficient solar collector concepts for given application, operation and climatic conditions with respect to economic parameters of the construction. A mathematical/theoretical model is always a simplification of realism to a certain degree or it is possible to model a system to a high degree of accuracy to extract the required information [157]. Several authors evolved simplified analytical models by considering the temperature independent solar cooker overall heat loss coefficient, absorber temperature distribution or temperature difference between absorber surface and heat transfer fluid, etc.

Pejack presented a mathematical model of thermal performance and shown that many of the variables like wind wall thermal resistance, latitude, reflector angle, mass of the food, clouds, etc. involved with solar cooking, have a significant effect on the food temperature and therefore on the effectiveness of cooking. The temperature needed actually cooking, depends upon the particular food [158]. Habeebullah et al. developed a mathematical model to solve energy equations by the help of forth order of Ranga–Kutta method. An oven type approach was introduced as an alternate for collecting the solar energy would drastically boost the overall cooker efficiency. A great advantage to use a glass sided solar oven over the base receiver pot was shown theoretically by simulation. It was proved theoretically that a base receiver is very sensitive to wind speed. So this type of solar cooker fails in high wind speeds, but the oven type receiver has proven to be practically independent of wind speed [31].

Binark and Turkman carried out the thermal analysis of a SBC using the forth order Ranga–Kutta method in Istanbul (Turkey) for a model named ITU-2. A theoretical investigation was carried out to determine the performance of box cooker by thermal analysis. The analysis is independent of numbers of cooking vessels placed in cooker. The theoretical results were found satisfactorily to experimental results [159]. El-Sebaii and Aboul-Enein presented a transient mathematical model which was based on analytical solution of the energy-balance equations using Cramer's rule for different elements of the box cooker. All the experiments were carried out in Tanta, latitude 30°47′N, Egypt. The model was discussed for a SBC with a one-step outer reflector hinged at the top of the cooker. The characteristic boiling time was found decreased about 30%, when the cooker was used at mid-day [32].

Funk and Larson presented a model to predict the cooking power of SBC based on three controlled (solar intercept area, overall heat loss coefficient and thermal conductivity of absorber tray) and three uncontrolled parameters (insolation, temperature difference and load). The model was presented and solved with help of simple energy balance equations to estimate the cooking capacity of box type cooker [160]. Terrés-Peña and Quinto-Diez have accessible a mathematical model of a SBC with multi-step inner reflector and the numerical results for two applications: (i) numerical simulation of operation of SBC with multi-step inner reflector and (ii) numerical simulation of a SBC with multi-step inner reflector for 10 h of process were analyzed. The mathematical model obtained from energetic analysis was formed for five differential equations system no linear and the fourth Runge–Kutta method was used to resolve it. The numerical solution of the equations system is obtained with computational software in C^{++}. The use of these techniques to solve the mathematical model is important to contribute in the evaluation and design of solar box cookers with multi-step inner reflector [161]. Ozkaymak tested a hot box solar cooker with three reflectors and a mathematical model was prepared. The energy balance equations applied to the components of SBC such as glass cover, enclosure air inside the cooker, cooking fluid, cooking vessels and

absorber tray. The equations were solved by Crammer's rule and build the model. A curved agreement was presented between the experimental and theoretical analysis [162].

Jaramillo et al. have designed a solar oven with the seven faces for inter tropical zones. The design was specially associated with a heavy concentration of solar radiation throughout the year. To analyze the optical performance of a solar oven, testing was carried out by using a scale model of cooker and a heliodon. A greater value of concentrator (1.95 for all days of the year) was achieved by the solar oven at noon [163]. Kurt et al. applied a new approach ANN for performance parameters of a SBC. The regression coefficients indicated that the artificial neural network (ANN) model can successfully be used for the prediction of the thermal performance parameters of a box type solar cooker with a high degree of accuracy [164]. Grupp et al. have designed a metering device for the determination of solar cooker use rate. The device was used to record the food temperature, ambient temperature and irradiance. Automatic data evaluation yielded the number of cooking cycles, cooking time, food "thermal mass" and the impact on fuel consumption and "GHG emission" compared to other cooking techniques. The solar cooker used meter which described the actual cooking time taken in terms of quantity of food cooked successfully, allowing the assessment of fuel savings and GHG emission reduction, compared to other cooking options [165].

9. Economics evaluation and ecological benefits of solar cooker

Among the various factors of mostly used of a SBC globally, is its lowest manufacturing cost with low cost of maintenance. Apart this subsidy is also provided on them for promoting in different countries. Some of the authors have been paid attention in this direction.

Kandpal and Mathur made and applied an approach to estimate the net present value (NPV) of a SBC by the following equation:

$$\mathrm{NPV} = \left(\frac{np - C_o\alpha}{d}\right)\left[\frac{(1+d)^t - 1}{(1+d)t}\right] - C_o \tag{1}$$

And minimum the number of meals to be cooked in a solar cooker so as to be economic by:

$$n_m = \frac{C_o}{p}\left[\alpha + \frac{d(1+d)t}{(1+d)^t - 1}\right] \tag{2}$$

and the pay back period of solar cooker by:

$$PP = \frac{C_o}{(np - \alpha C_o)} \tag{3}$$

where C_o is the large spread in the price of solar cooker, P is the money value of the fuel saved per cooked meal, α is the fraction of the initial investment which is spent on the maintenance of the solar cooker each year, n is the number of years.

Authors made the sensitivity analysis of the economics of a typical SBC [166].

Nahar and Gupta have discussed the significant role of solar cooers in conserving traditional cooking fuels. Different solar cookers (a solar oven, a hot-box solar cooker and a solar cooker with tilted absorber) have been examined and evaluate their potential impact on energy savings. The energy required per person for cooking was estimated about 900 kJ of fuel equivalent per meal. Solar cookers may be used for five people and can save about 2250 kJ/meal. Use of the discussed cooker saved 45.07, 39.38 and 42.67%, respectively of the total energy required for cooking for a family of five. The PBP's have been computed by:

$$n = \left\{\frac{\log(E-M)}{a-b} - \frac{\log[(E-M)/(a-b) - C + S]}{\log[(1+a)/(1+b)]}\right\} \tag{4}$$

where a = annual interest rate, b = energy and maintenance inflation rate, C = cost of the solar cooker, E = energy savings per year, M = maintenance cost per year, n = payback period, and S = Government subsidy [167].

Nahar et al. carried out performance testing of an improved community size solar cooker and compared with a hot box solar cooker with a single reflector. The cooker was found to cook the meal for 80 persons. The financial analysis of the cooker was carried out by considering the annual interest, maintenance cost and inflation in fuel prices. The PBP's varied between 1.16 and 3.85 years in increasing order W_{rt} the fuels, firewood, coal, electricity, LPG and kerosene. The estimated life was about 15 years [168], while Nahar has been fabricated and tested some different designed solar cookers in different years. The overall efficiency of the solar cookers was 29.5%, 28.9% and 27.5% respectively. The PBP's varied between 1.28 and 4.82 years depending upon the cooking fuel replaces. For different cookers the saved energy was also estimated maximum of 5175 MJ of energy per year. The PBP's were in the increasing order with respect to fuels such as firewood, coal, electricity, kerosene and LPG. The estimated life was about 15 years for both cookers. The use of the non-tracking solar cooker would result in a reduced release of CO_2 to the environment. The cost ranges of the cookers were Rs.1500.00 to Rs. 10000.00 for small to large size cooker. The PBP, 1.58 years (W_{rt} electricity), 4.89 years (W_{rt} kerosene) has been calculated by considering 10% annual interest, 5% maintenance cost and 5% inflation in fuel prices and maintenance cost [169–171].

Nandwani highlighted the ecological benefits of a solar cooker. A study was carried out to estimate the energy used for cooking in Costa Rica and compared with advantages and limitations of solar ovens with conventional firewood, electric stoves, firewood and CO_2 savings per year was outlined for year 2005 from various surveys by author [172]. Kumar et al. have been carried out a financial evaluation of a SBC using the cost function for its capital cost. Expression for different financial performance, as a maintenance cost estimation of the number of meals cooked per year and financial evaluation was calculated. A correlation was established between capital cost (INR) and exposed area of the glazing [173]. Escobar have shown the use of a low budget SBC through ecological benefits. The cost of the cooker was <US$ 20 and developed at the School of Physics seeking to reduce the consumption of wood as an energy source. According to National statistics this source of energy represents 53% of the primary energy consumed in the country. The economics savings by using a SBC in terms of wood burning and electricity were properly highlighted [174].

Wareham showed that cooking with fossil fuels causes health problem and ecological damage in the developing countries. A SBC cooker requires low cost and good performance to replace these fuels. It was shown that the solar cooker must have high quality and to be sold in high quantity, price should be low. So the poor one can also afford, subsidies should be there by government and must be user friendly i.e., affordable, light in weight, weather resistance, easy to use and obviously a family size. Point it towards the sun, when there is off-sunshine; use the cooking resources you saved [87]. Carmody and Sarkar reflected towards the small scale applications of solar energy which were not brought to proper utilization due to research and development much concentrated on highly technical, capital intensive applications of solar energy. The authors examined a SBC for its economic viability

Table 4
Performance of cooker “A” and “B” with load and without load.

Time (h)	T_{amb} (°C)	H_s (w/m^2)	T_{stag} (A)	F_1 (A)	F_2 (A)	T_{stag} (B)	F_1 (B)	F_2 (B)
12	41	810	130	0.109	0.44	139	0.120	0.39
13	43	767	135	0.119	0.36	144	0.131	0.39
14	43	760	136	0.122	0.42	147	0.136	0.41
15	30	800	126	0.120	0.40	135	0.131	0.40
16	31	726	128	0.133	0.44	138	0.147	0.40
17	29	770	129	0.129	0.40	137	0.140	0.39

costs and benefits on the households and community levels and how they may contribute to economic development [175]. Purohit et al. estimated at about 75 million (2001) potential of solar cookers. The total potential (P_{sc}) of using box type solar cooker for supplementing domestic cooking in India can be estimated by a few characteristics of households in country. The nomograph was used to determine the number of total households in urban areas (as a fraction of total households) who can use box type solar cookers [176].

Wentzel and Pouris have carried out impact studies and use rate studies by a number of different organizations since the inception of the project; impact studies indicate that solar cooker have a positive development impact on households through fuel energy and time savings. Author made some suggestions like as promotion of a SBC as an additional cooking option. They should well made product comparable to the other households cooking appliance and user most be well supported with information as well as technical backup in the form of products guarantee so that people can believe that a SBC can actually cook the food [177]. Kimambo made an attempt to resolve the issues like appropriate types of solar cookers for specific locations, optimum size/capacity, types of materials to be used, optimal design and affordable cost, a comprehensive study involving theoretical review, development work, experimental testing and evaluation of solar cookers was

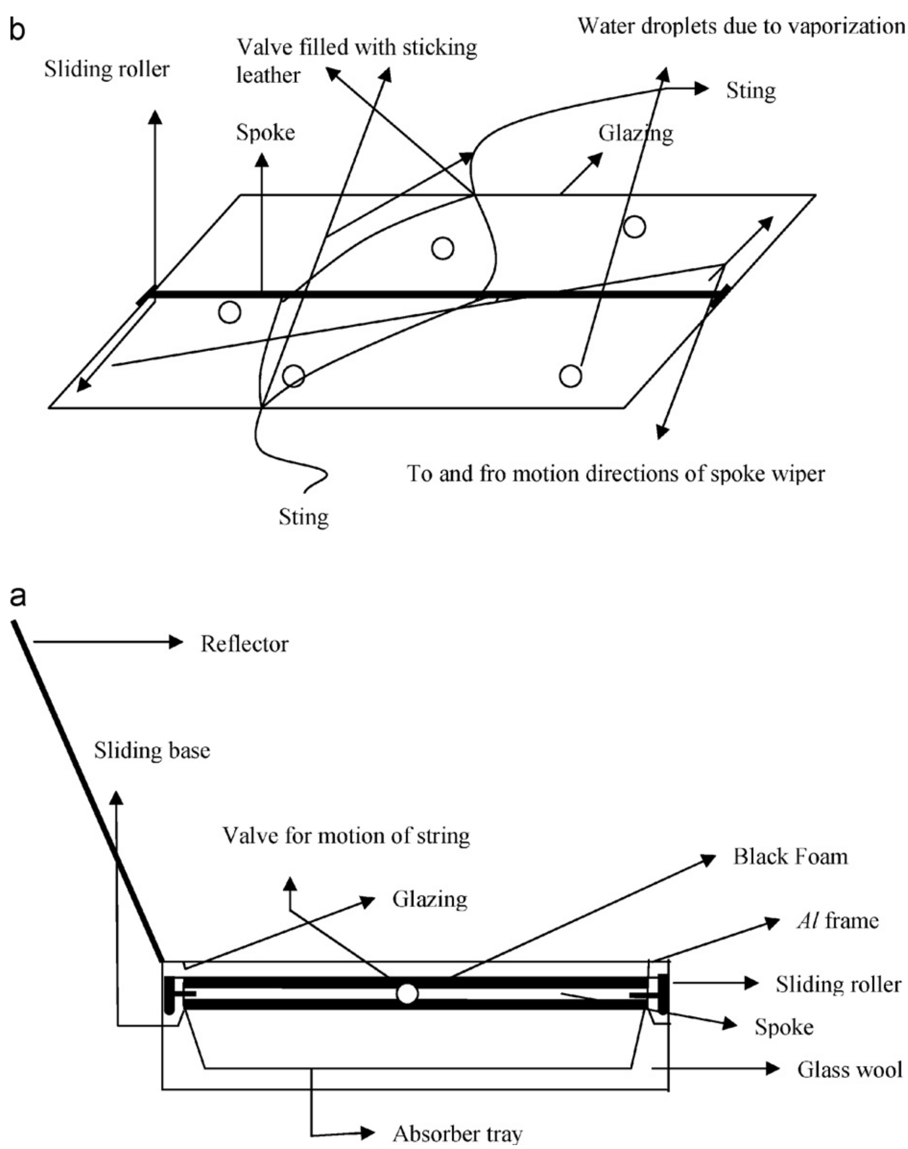

Fig. 3. (a) SBC with sliding wiper mechanism. (b) Sliding mechanism on bottom of glazing of a SBC.

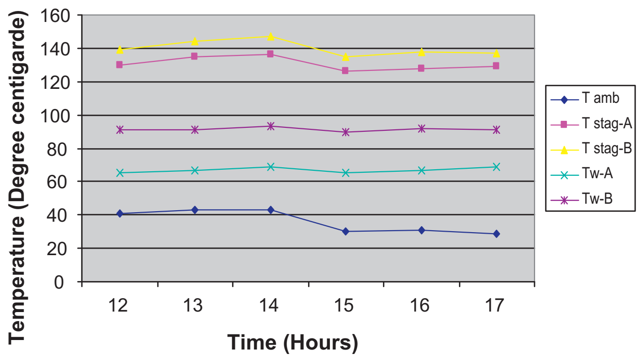

Fig. 4. Thermal performance of cooker "A" and "B".

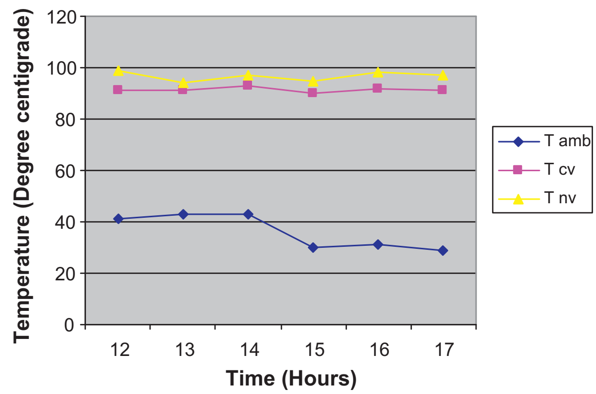

Fig. 6. Thermal load testing of box cookers with conventional and modified cooking vessel.

conducted for several years on six different types of solar cookers, which are the 'Sun Stove' box cooker, wooden box cooker, panel cooker, reflector cooker with unpolished aluminium reflectors, reflector cooker with polished aluminium reflectors and reflector cooker with glass mirror reflectors. As a guiding tool, reflector cookers offer best comparative performance in areas with longest durations of clear sky, panel and collector cookers under moderate cloudy conditions and box cookers under very cloudy conditions [178]. Luna and Huelsz have optimized an opto-geometrical design of a solar oven for the inter-tropical zone and evaluated for the cooking process. Three basic Mexican meals: beans, nixtamal, and corncobs were cooked successfully in the oven. A conservative estimation was shown that the wood savings per oven was 850 kg per year. The designed oven was observed for efficiency improvement by reducing heat losses [179]. Dendz and Atik have made a study on solar energy which attracts more attention due to its various advantages over the other alternative energy sources. This energy source is used via various systems and solar cookers are one of them. In the particular study employability of solar cookers in Karabuk was investigated. For this purpose, a box type solar cooker was made and tested in Karabuk weather conditions. Several types of food were cooked in the experiments and it was concluded that solar cookers can be used in Karabuk and save the energy [180].

10. Performance studies of a solar cooker with wiper mechanism

A simple box cooker was fabricated to evaluate the cooker performance with wiper mechanism. A flexi sliding type arrangement has been introduced with a roll of black foam or black cushion on a spoke, which works like a wiper on the bottom part of internal glazing to remove the vapor droplets during the cooking. This arrangement became very supportable to improve the performance of a SBC. It works manually and operated through a strong sting, which passes through a minor hole of 1 mm, diameter, provided in the centre of length and width dimensions of SBC at the top of absorber tray. To minimize the heat losses hard leather was filled in the holes and sticked with a good adhesive. The length of the sting is triple the length of the absorber tray.

The performance testing of the modified box cooker has been carried out experimentally. For experimental procedure two box cookers with same specifications were taken one simple box cooker "A" and one was with wiper mechanism "B". There was an additional reflector in cooker "B" to get extra heat energy. Two figures of merit and cooking power has been calculated and found to meet international standard [17,18]. For sensible heat testing 1 kg

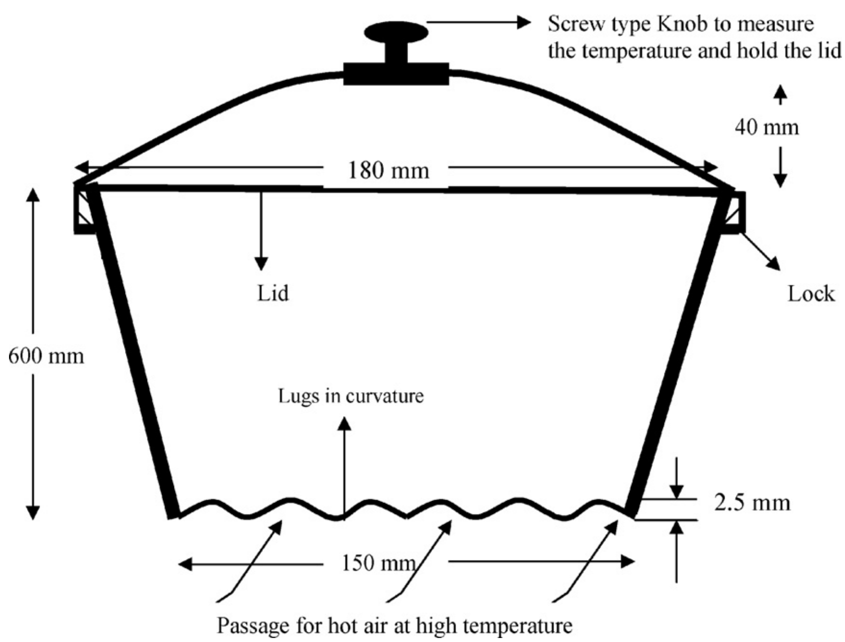

Fig. 5. A modified cooking vessel for a SBC.

of water was taken as a cooking fluid. The testing of cooker was carried out on a typical solar noon on 10.07.2010, from 12.00 to 17.00 P.M. inside the campus building of Moradabad Institute of Technology, under the climate conditions of Moradabad (latitude – 28°58′north and longitude – 78°47′east) Uttar Pradesh (Table 4 and Figs. 3 and 4).

Comments: Comparing the performances curves of both cookers it can be noticed that the new modified cooker with wiper mechanism achieved good cooking temperature in less time than a simple box cooker of same specifications.

Solar box cooker	Efficiency (%)	Power (W)
Simple constructed box cooker “A”	60	70
Modified box cooker “B”	67.66	78

The modified cooker is low in price with comparison to other present designs of box cookers and is easy to fabricate and use, low maintenance, easy cleaning and efficient cooking in low temperature. Quality cooking of every type of eatables is possible. It can be operated by any person due to simple construction and user friendly. The present SBC has been found good for cooking in Moradabad. Further steps required to optimize the design modified box cooker are understudied.

11. Performance studies of solar cooker with modified cooking vessel

A cooking vessel has been modified to reduce the cooking time taken by a SBC. The trapezoidal shape of cooking vessel absorb a good amount of solar radiation due to its exposed surface area and made of aluminium with a 150 mm bottom end diameter and 180 mm top end diameter. A series of lugs in a curvature form at the bottom of vessel is provided for better heat transfer. The lid becomes hot and will generate a current of hot air, which circulates inside the box cooker. The heat carrying by this hot air circulation, reaches to the food via the most sides of the vessel. A heat transfer between food and the lid takes place by means of convection in the air layer between the food and the lid. The air convection was effective in transferring heat from the food to the lid and vice versa. The total depth of the cooking vessel is 600 mm + 40 mm. The radius of curvature of a lug is 2.5 mm. To measure the temperature of cooking fluid stored in the modified cooking vessel during the testing a lid holder openable knob (screw threaded) has been provided on the top of cooking vessel. There is also a locking system of lid to the cooking vessel for proper closing. The testing was carried out to estimate the cooking power [18] (Figs. 5 and 6).

Comments: The new modified cooking vessel has been observed to achieve good cooking temperature in less timing than a conventional cooking vessel. The modified cooking vessel was found to reduce the cooking time for 20 min to cook the pulse in the comparison of conventional type cooking vessel. The cooking power has been also improved from 70.60 W (conventional vessel) to 79.80 W (new vessel) of solar cooker was used for testing. The quality of cooked food in new cooking vessel was found to be good ripe and tasteful.

12. Conclusion

From the review it is concluded that every element of a solar cooker have great importance and direct effects the performance of cooker in any climate conditions. For quality cooking no one parameter has been eliminated among these. Author is concluded by the literature review that the following should be limitations of the characteristics of a solar cooker for efficient performance.

Consideration for a family of five members (India)

Mirror Booster – should be two
Glazing – should be double
Absorber tray – wxpanded enclosure with one mm thickness and blackened
Cooking capacity – two or three food can be cooked simultaneously in separate cooking vessel
Normal size – 70 × 70 cm^2
Insulation – glass wool for bottom and TIM for insulation in between the glazing
Phase Change Material (if any) – stearic acid (commercial grade)
Limitations for acceptance – BIS and ASAE
Cost – should be around 1000–1500 (INR)
Pay back period – at least 18 months
Further changes can be done accordingly to the household and climate conditions.

Various other major consequences are there such as real pollution saver, cooking fuel saver, electricity saver, no major attention is required, time saver, money saver, a better and more nutritious cooked food because of its slow cooking design. On the other side two approaches made by author have been found successful to reduce the cooking time with efficient cooking for a box cooker. Author is requested to promote the solar cooker by all and save power and fuel.

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